Numerical Investigation of Resistance Reduction of Fishing Boat by Improving Stern Part

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***Abstract*- In recent years, to achieve a goal of reducing greenhouse gas, a fishing boat which is very economical on gas should be needed. Over the last two decades, improvements of bow part in fishing boat have been researched to reduce water resistance. Moreover, stern End Bulb research took place mostly in Japan. No one finds universal knowledge for reducing drag resistance because many fishing boats run with individual catching styles for each fish. It is also difficult to appropriate some techniques in cruise ship and tanker for fishing boat. In this study, to reduce drag resistance, improvement of body line and addition product at stern part were examined. All of the cases proposed in this study could reduce water resistance. The maximum reduction rate was around 15 to 20% comparing with the basic form (original case). Some useful improvements were found based on Computational Fluid Dynamics (CFD) works and flow visualization by Particle Image velocimetry (PIV) technique.**

Keywords*- *Fishing boat*; *Stern*; *Resistance reduction*; *CFD

I. INTRODUCTION

In recent year, to achieve a goal of reducing greenhouse gas, a fishing boat which is very economical on gas should be needed. A magnitude of market for a fishing boat is not so large compared with a tanker and a ferry. Many of fishing boats run with individual catching styles for each fish at full capacity in all seasons. Therefore fishermen do not have enough time to improve a fishing boat and therefore they prefer a localized improvement to reduce a waste of cost and fuel. On the other hand, the huge tsunami caused by the Tohoku earthquake carried away many fishing boats offshore. It is required that a new fishing boat based on ecological and economical design is proposed and developed as soon as possible.

Over the last two decades, to reduce water resistance, some improvements of bow part in fishing boat have been researched [1-3]. Early stern end bulb research took place mostly in Japan [4-7]. On the other hand, in recent years, researchers [8-9] have conducted numerical works related with stern part improvement for reducing drag. The CFD-based hull-form hydrodynamic optimization was automatically and efficiency conducted.

However, researches on stern part are not enough to optimize design for a fishing boat and then there are many problems for improving of a fishing boat. No one finds universal knowledge for reducing drag resistance because there are so many kinds of fishing style for each fish. Moreover, it is difficult to appropriate some techniques in cruise ship and tanker for fishing boat.

In this study, to reduce drag resistance in column water and wave motion, improvement of body line and addition product at stern part are examined. Some improvements are investigated and a useful design of stern part for fishing boat is also found based on CFD numerical works and flow visualization by PIV technique.

II. NUMERICAL METHOD

A. *Overview of Hybrid Scheme*

In our previous work, An Eulerian scheme with Lagrangian particles has been developed [10]. Figure 1 shows illustration of Eulerian scheme with Lagrangian particles for computing a multiphase flow. This method has hybrid techniques coupling grid based method based on CIP method with particle based method based on SPH method. Density function ϕ_i (i=1: gas, i=2: water, i=3: solid) is defined on node of Eulerian grid in all phases. Time evolution of the density function is advanced by advection equation of ϕ_i. To compute accurate interface between different phases, two kinds of Lagrangian particles having density function ϕ_p are employed on Eulerian grid in which physical values are defined on staggered grid system. One is SPH particle to compute solid deformation and motion for solid phase. These particles play an important role in tracking solid motion deformation. The particles can be computed by SPH method. The other is free surface particle to track interface between water and gas. The free surface particle is massless particle and they should be located near free surface where gradient of density function is maximum. Their distribution is only concentrated near free surface. Time integration of free surface particles is computed by 4th Runge Kutta method. These free surface particles and SPH ones can contribute to correct numerical error of density function ϕ_i coming from time integration on Eulerian grid. Adapting complicated free surface configuration, redistribution process of Lagrangian particles is necessary to keep effectiveness and stability and to enhance numerical accuracy of tracking interface during calculation time. This process is only executed when volume error for water region exceeds a limit condition to work well.

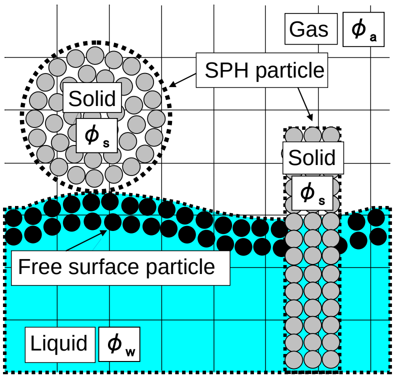

Fig. 1 Illustration of Eulerian scheme with Lagrangian particles
(ϕ_i indicates density function, Lagrangian particles are located on Eulerian grids.)

B. Governing Equations

The governing equations for fluid phase consist of the mass conservation equation, incompressible Navier-Stokes equation and the equation of continuity, density function for *i*-phase and its advection equation. The equations computed by grid based method are expressed as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\mu}{\rho}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + g_i + \bar{F}_{fsi} \tag{2}$$

$$\frac{\partial \phi_I}{\partial t} + \bar{u}_j \frac{\partial \phi_I}{\partial x_j} = 0 \tag{3}$$

where, u_i is the velocity, μ the coefficient of fluid viscosity, ρ the fluid density, P the pressure, F_{fsi} the fluid-structure interaction, g_i the acceleration due to gravity, τ_{ij} the SGS stress term, and ϕ the density function. To reduce model parameters, the SGS stress term is solved by using the dynamic SGS model. Time splitting technique is employed for multiphase flow. More details are provided [11].

On the other hand, the governing equations for solid phase are the continuity and momentum equations computed by SPH method as follows:

$$\frac{D\rho}{Dt} + \rho \frac{\partial u^i}{\partial x^i} = 0 \tag{4}$$

$$\rho \frac{Du^i}{Dt} = \frac{\partial \sigma^{ij}}{\partial x^j} + g^i - F^i_{fsi} \tag{5}$$

where S^{ij} is the density, u_i the velocity, $P = -\sigma_{kk}/3$ the position vector of vector j components, the stress tensor of the solid phase, and F_{fsi} the fluid structure interaction term. These equations are discretized based on SPH method. The stress tensor σ_s^{ij} in (5) is given by

$$\sigma_s^{ij} = -P\delta^{ij} + S^{ij} \tag{6}$$

where S^{ij} is the deviatoric stress tensor, the pressure solved by the Poisson's equation. The pressure with specified jump conditions is solved by the Poisson's equation given by

$$\nabla \cdot \left(\frac{\nabla P^{n+1}}{\rho^*} \right) = \frac{\nabla \cdot u^*}{\Delta t} \tag{7}$$

where $*$ denotes a physical value after the advection step. The pressure for solid phase can be obtained by this equation and be applied in solving a solid deformation.

The fluid structure interaction F_{fsi} is solved by acceleration obtained from the pressure on SPH particles interpolated using the pressure on grids solved by (7). In the model, the fluid structure interaction F_{fsi} in (2) and (5) can be given by the following equation:

$$F_{fsi}(\mathbf{r}_a) = -\frac{1}{\rho(\mathbf{r}_a)} \sum_b m_b \frac{P(\mathbf{r}_b)}{\rho(\mathbf{r}_b)} \nabla_a W(\mathbf{r}_a - \mathbf{r}_b, h) \tag{8}$$

A ship motion can be solved by using information obtained from SPH particles because a ship hull consists of SPH particles capturing motion and deformation of a ship. Therefore, the 3D motion of a ship hull is represented by describing translation and rotation of the center of gravity of a ship hull by using the quaternion to avoid the Gimbal lock phenomenon.

C. Validation

Figure 2 shows comparison of total resistance including friction and pressure in column water at each Froude number (*Fr*). The numerical result is in good agreement with the experimental result. There is a slight difference between experimental result and computational one when *Fr* is larger than 0.3. The difference was caused by water splashing at the front of bow and pressure fluctuation due to small scale disturbance of free surface generated by stern edge. The fine grid and smaller size of free surface particle should be set in initial condition of future work.

Figure 3 shows one snapshot of fishing boat motions in heading wave. The fishing boat is oppositely running in progressing wave. The motions such as heave and pitch can be reproduced by the present model and the splashing and droplets caused by the bow slamming occurred near the free surface. They can be captured by free surface particles in this model. Figures 4 and 5 show comparison of heave and pitch motions in heading wave, respectively.

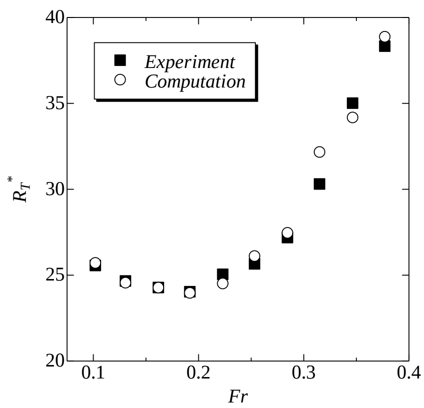

Fig. 2 Comparison of total resistance in column water

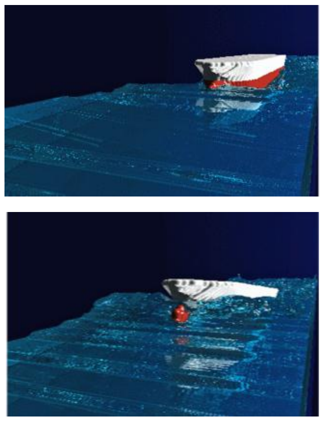

Fig. 3 Snapshots of fishing boat motions in heading wave

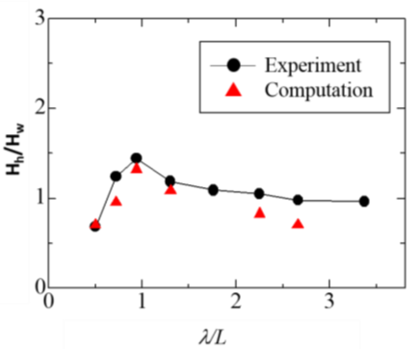

Fig. 4 Comparison of heave motion in heading wave

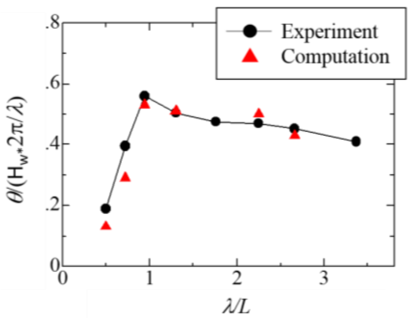

Fig. 5 Comparison of pitch motion in heading wave

The wave height is *H/L*=0.06 where *L* is wave length and the Froude number is 0.34. The numerical results are generally in agreement with the experimental results. The heave and pitch motions reach maximum value when λ/L =1 and then they are gradually decreasing with increasing λ/L .

III. FLOW VISUALIZATION AROUND STERN BY PIV TECHNIQUE

To investigate flow field around stern part of fishing boat, the PIV technique was performed using YAG laser and high speed video camera. The high speed video camera (500 fps) can capture a large number of particles simultaneously within a target area in flow field. Velocity field can be obtained by calculating movement of each particles during a captured increment time. The ship prototype model using a transom stern was 1/14 scale model in the experiment. The model was set in circular water tank in Hiroshima University.

Figure 6 shows *x*-*y* and *x*-*z* velocity fields calculated by the video images captured by the video camera. The Froude number was set to 0.225. The flow separation was generated at the side edge of the stern part. The large cavity area where the flow velocity is low, also emerged behind the stern. The separation flow filed causes strongly differential pressure between the bow and stern parts and then the resultant water resistance is generated. The result means that configuration of the stern part should be gently smooth to reduce velocity gradient at separated shear area.

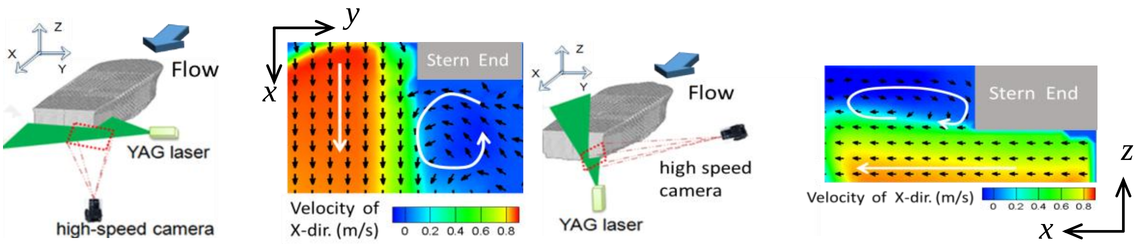

Fig. 6 PIV system and one example of calculated velocity filed around stern part

IV. REDUCTION OF WATER RESISTANCE BY IMPROVING STERN CONFIGURATION

Considering flow field around stern part in the previous chapter, four different kinds of configuration at stern part were proposed as shown in Fig. 7 to avoid a strongly separated shear flow. The reduced displacements of Stern 1, Stern 2, Stern 3 and Stern 4 are -1.3, -3.7, -9.5 and -4.5 respectively.

Figure 8 shows comparison of total resistance including both pressure resistance and friction resistance in column water. The vertical axis indicates the ratio of water resistance to the original case (basic form). The snapshots of free surface motion around the ship in column water are shown in Fig. 9. The Froude number is 0.384. The fishing boat consists of 20,000 to 30,000 SPH particles. The total number of the free surface particles near the free surface is 400,000 to 90,000. The particle size is 0.0025 *L*pp, where *L*pp is the ship length. The time increment is 10^{-4}(s). It can be seen that all of the proposed stern configuration can reduce the water resistance in column water compared with the original case. The maximum reduction rate is 9% or more in Stern 1 although the reduced displacement is relatively small compared with other cases.

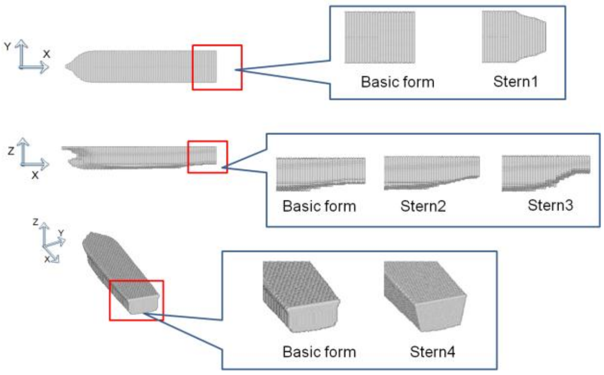

Fig. 7 Several kinds of the improved stern part of the fishing boat

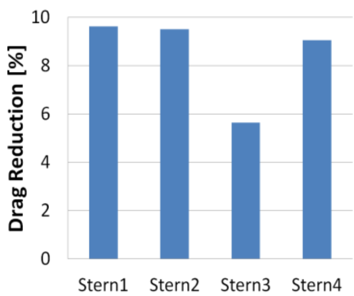

Fig. 8 Comparison of drag reduction between the basic form and improved sterns

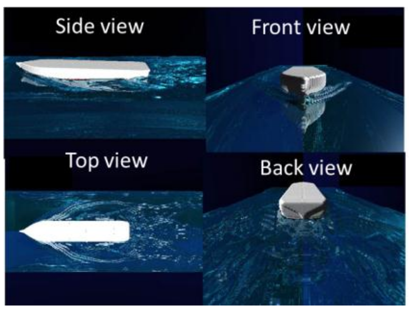

Fig. 9 Snapshots of free surface motion around fishing boat in column water (*Fr*=0.384)

Figures 10 and 11 show comparison of velocity field between the basic form case and Stern 1 case around the fishing boat at y-z and x-z sections near free surface. In Stern 1, the stagnation area near the separated shear layer at the stern part is relatively small and the velocity gradient is gently mild, especially at x-z section, compared with the basic form case.

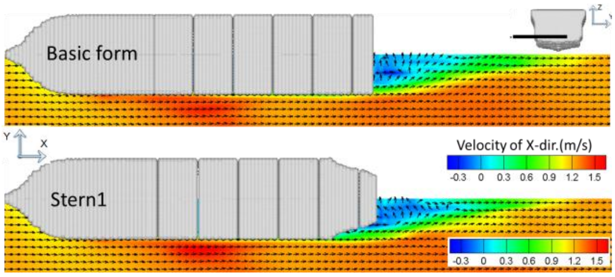

Fig. 10 Velocity filed around the fishing boat at y-z section near free surface (Top: Basic form, Bottom: Stern 1)

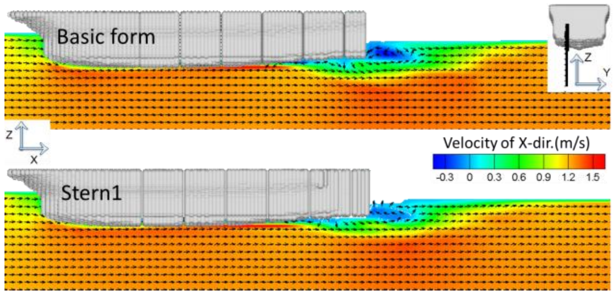

Fig. 11 Velocity filed around the fishing boat at x-z section (Top: Basic form, Bottom: Stern 1)

V. REDUCTION OF WATER RESISTANCE DUE TO ADDITION PRODUCT AT STERN

In the previous section, it is clear that some improvements of the body line at the stern part of the shipping boat can be optimized to reduce the water resistance. In this section, effect on an addition product at the stern part is examined without a drastically exchange of the body line. This allows us to reduce cost and time for reproducing and improving the shipping boat.

Some researches on an addition product at stern part were conducted based on CFD and experiment, e.g., Miyata et al. [4-7]. The addition product at stern part has complex deformation and some experienced parameters which are difficult to optimize at a design ship speed related with Froude number. Therefore, more simply modified addition products with low cost should be needed for industry area of a fishing boat in which the market is not so large in both the domestic market and the overseas one.

In this study, reduction of water resistance due to a simplified additional product such as a board type and small cubic type is investigated. Figure 12 shows the proposed addition product in this research. SEB1 is the vertical plate located at the center line of the ship width. SEB2 is the horizontal plate located at near the free surface and SEB2down is located near the free surface. SEB3 is combined with SEB1 and SEB2. SEB4 is horizontal plate with V-shape. SEB5 is combined with SEB1 and SEB4. SEB6 is the small cubic box located at the center line of the ship. Each of them is attached at the stern end part of the basic form of the fishing boat. The range of increased displacement is +0.1 to +0.54%.

Figure 13 shows comparison of drag resistance of fishing boat in column water. The Froude number is 0.384. The drag resistance means the rate of reducing resistance due to the addition product to the basic form (original case). It can be seen that all of the addition products can reduce the water resistance. The averaged drag reduction is approximately 10% and the maximum one is 15% or more in SEB2down. To clarify the reason why SEB2down could be a useful addition product for reducing the water resistance, the streamline and velocity field are investigated as shown in Figs. 14 and 15, respectively.

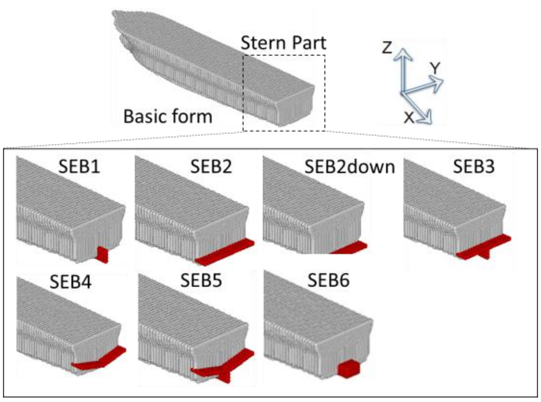

Fig. 12 Proposed addition products at stern part describing by SPH particles

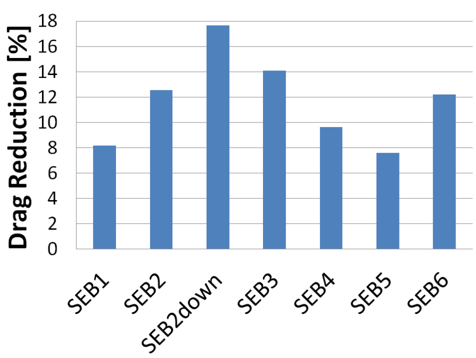

Fig. 13 Comparison of drag reduction between the basic form and the addition product case.

In the basic form, the large vortex was generated from the bottom of the stern part where the velocity is considerably lower than that in the bow part. On the other hand, in SEB2down, the streamline is relatively smooth and the large separated flow does not occur at the stern part. This is because the horizontal plate located at the bottom edge of the stern part can play a role of controlling the separated flow and the vortex generated from the edge of the bottom of the stern part.

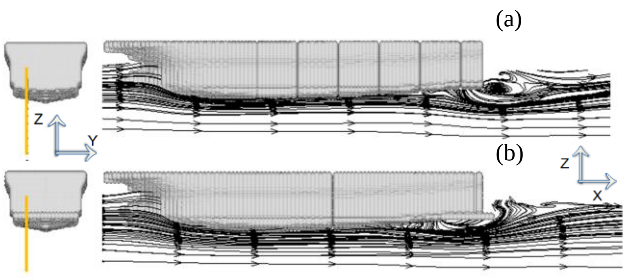

Fig. 14 Streamlines around the stern (a) Basic form (b) SEB2down

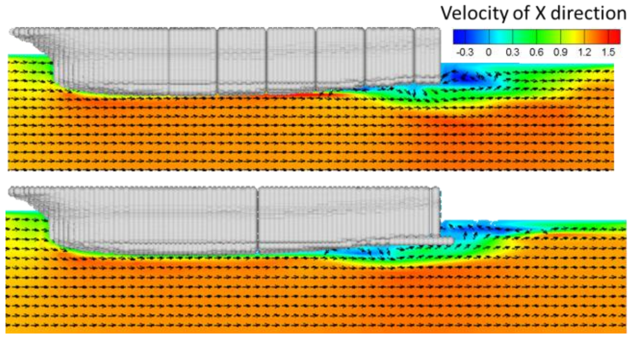

Fig. 15 Velocity field around the stern (a) Basic form (b) SEB2down

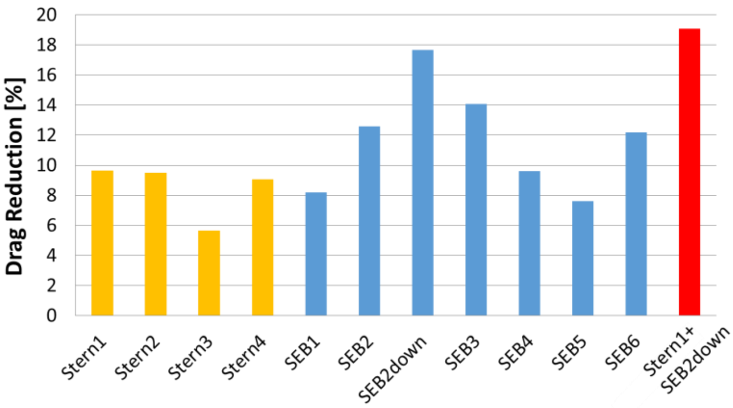

Fig. 16 Comparison of drag resistance in all cases

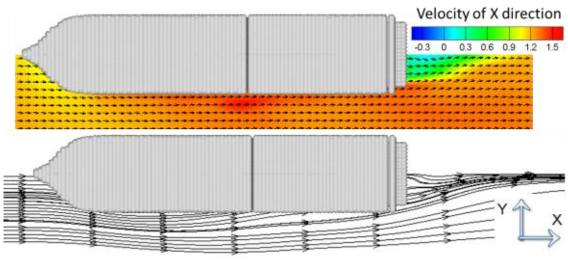

Fig. 17 Velocity field and streamline in x-y plane

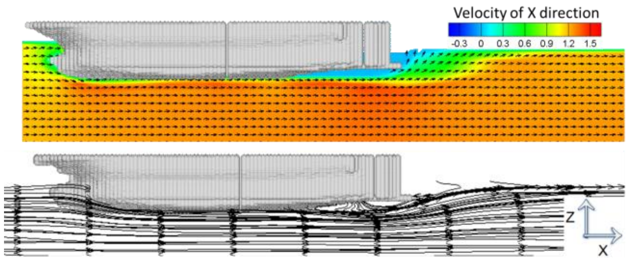

Fig. 18 Velocity field and streamline in x-z plane

To make more reduction of water resistance, both the stern configuration and the addition product can be combined. In this study, Stern1 and SEB2down which can relatively reduce the drag resistance, were combined. Figure 16 shows comparison of drag reduction rate in all cases including the combined base (Stern1+SEB2down). The maximum reduction rate is around 19% in Stern1+SEB2down.

Figures 17 and 18 show velocity field and streamline around the stern in the combination case, Stern1+SEB2down, respectively. The streamline is very smooth compared with the basic case, Stern1 and SEB2down. The velocity gradient is gradually smaller and it was drastically improved. This result means that this case is better combination for reducing the water resistance compared with separate contribution by each product and body line.

VI. CONCLUSIONS

To reduce water resistance by improving a body line of a stern part of a fishing boat and addition product at stern edge, flow filed around stern part was visualized by PIV technique and numerical investigations were also conducted by our developed CFD code, Eulerian scheme and Lagrangian particles. As a result, the increasing water resistance was strongly related with the separated flow and the vortex field around the stern part of the fishing boat. To control the separated flow at the stern edge, several body lines of the stern part and the additional products (total cases are 30) were examined and also the drag reductions were compared. All of the cases proposed in this study can reduce the water resistance and the flow field and the streamline around the stern part can be smooth and the velocity gradient can also be gently decreased. The maximum reduction rate is around 15% to 20% compared with the basic form (original case) in the combination of Stern1 and SEB2down. In future effort, water resistance of a fishing boat in wave motion should be investigated.

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